

(12) **United States Patent**
Milch

(10) **Patent No.:** **US 9,349,182 B2**
(45) **Date of Patent:** **May 24, 2016**

(54) **3D INTRAORAL MEASUREMENTS USING OPTICAL MULTILINE METHOD**

6,510,244 B2 1/2003 Proesmans et al.
6,754,370 B1 6/2004 Hall-Holt et al.
7,126,699 B1 * 10/2006 Wihl et al. 356/625

(75) Inventor: **James R. Milch**, Penfield, NY (US)

(Continued)

(73) Assignee: **Carestream Health, Inc.**, Rochester, NY (US)

FOREIGN PATENT DOCUMENTS

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 658 days.

EP 2 051 042 B1 11/2010
JP 2009-098146 A 5/2009
WO 2011/013373 A1 2/2011

OTHER PUBLICATIONS

(21) Appl. No.: **13/525,590**

Guhring, Jens "Dense 3-D surface acquisition by structured light using off-the-shelf components", Videometrics and Optical Methods for 3D Shape Measurement, Proceedings of SPIE, vol. 4309 (2001) pp. 220-231.

(22) Filed: **Jun. 18, 2012**

(65) **Prior Publication Data**

US 2013/0120533 A1 May 16, 2013

(Continued)

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/293,308, filed on Nov. 10, 2011.

Primary Examiner — Christopher S Kelley
Assistant Examiner — Deirdre Beasley

(51) **Int. Cl.**
H04N 13/02 (2006.01)
G06T 7/00 (2006.01)

(57) **ABSTRACT**

(52) **U.S. Cl.**
CPC **G06T 7/0057** (2013.01); **G06T 7/0065** (2013.01); **G06T 2207/10016** (2013.01); **G06T 2207/10152** (2013.01); **G06T 2207/30036** (2013.01)

A method for mapping a sensor pixel array to an illumination pixel array according to a surface forms a group mapping by assigning each pixel to a corresponding group, each group with p adjacent pixels on the illumination array and each ordered set having k groups, by projecting and recording a sequence of group index images. Each group index image has, in at least two of the groups, no illuminated pixels and in fewer than (k-1) groups, from 2 to (p-1) adjacent illuminated pixels. The sequence of group index images uses pixels from each of the k groups. At least p multiline images are projected and recorded, wherein each multiline image projects a line within each group. Lines in the multiline images are correlated according to the group mapping and the correlation stored in memory. Integers k and p are greater than or equal to 3.

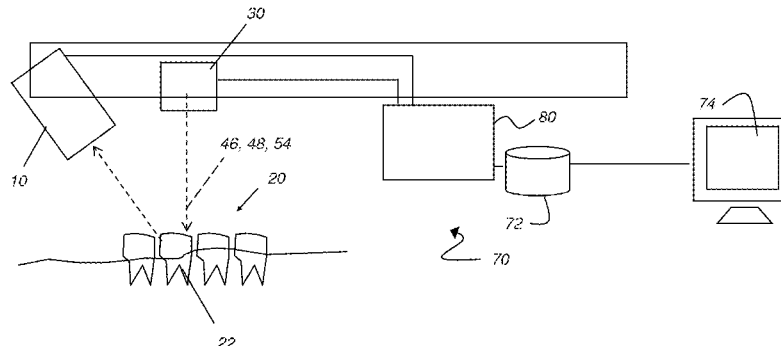
(58) **Field of Classification Search**
CPC A61C 9/006; G06T 7/0057; G06T 2207/30036; G06T 2207/10016; G06T 2207/10152; G06T 7/0065; H04N 13/02
USPC 348/45
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,372,502 A * 12/1994 Massen et al. 433/215
5,650,621 A * 7/1997 Tsuneta et al. 250/311

20 Claims, 23 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

7,146,036 B2 12/2006 An Chang et al.
 2005/0046873 A1* 3/2005 Suzuki 356/605
 2005/0099638 A1* 5/2005 Quadling et al. 356/603
 2005/0254726 A1 11/2005 Fuchs et al.
 2007/0057946 A1 3/2007 Albeck et al.
 2007/0091319 A1* 4/2007 Sonda et al. 356/600
 2009/0103103 A1* 4/2009 Berner 356/497
 2009/0238449 A1* 9/2009 Zhang et al. 382/165
 2009/0322859 A1 12/2009 Shelton et al.
 2010/0034429 A1 2/2010 Drouin et al.
 2010/0085636 A1 4/2010 Berner
 2010/0253773 A1 10/2010 Oota et al.
 2010/0268069 A1* 10/2010 Liang 600/425

2010/0311005 A1* 12/2010 Liang 433/29
 2011/0050859 A1 3/2011 Kimmel et al.

OTHER PUBLICATIONS

S. Logozzo, G. Franceschini, A. Kilpelä, M. Caponi, L. Governi, L. Blois: A Comparative Analysis of Intraoral 3d Digital Scanners for Restorative Dentistry. *The Internet Journal of Medical Technology*. 2011, vol. 5, No. 1, DOI: 10.5580/1b90, 19 pages, <http://www.ispub.com:80/journal/the-internet-journal-of-medical-technology/volume-5-number-1/a-comparative-analysis-of-intraoral-3d-digital-scanners-for-restorative-dentistry.html>.
 International Search Report mailed Feb. 1, 2013 for International Application No. PCT/US2012/052178, 2 pages.
 Supplemental European Search Report, Application No. EP12847432, Jun. 19, 2015, 2 pages.

* cited by examiner

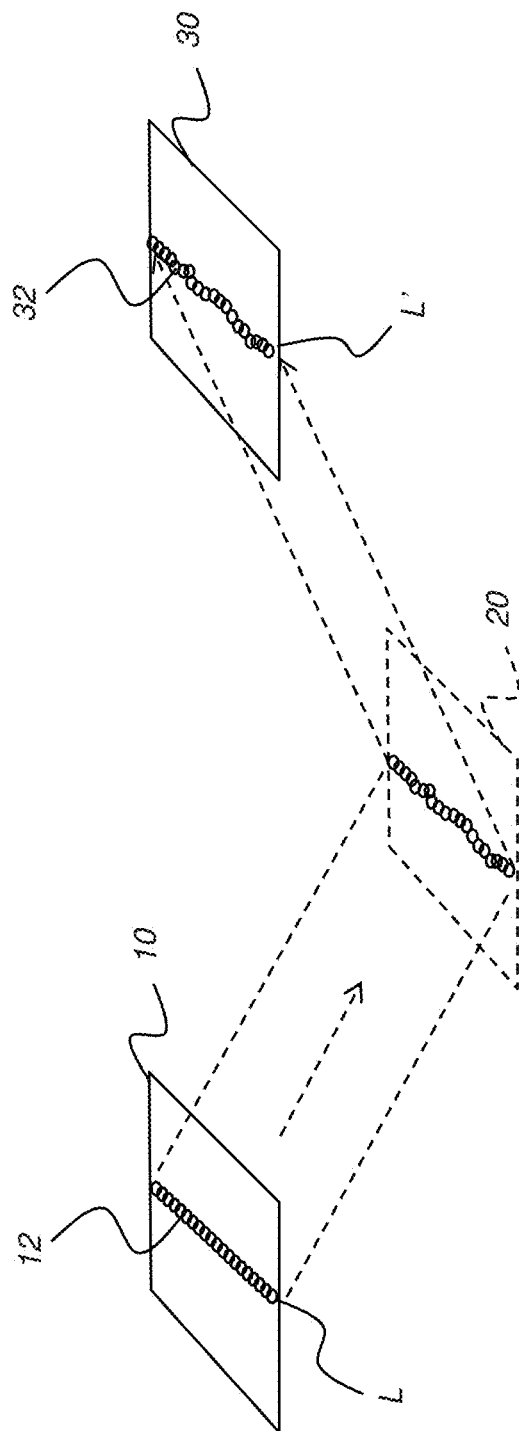


FIG. 1

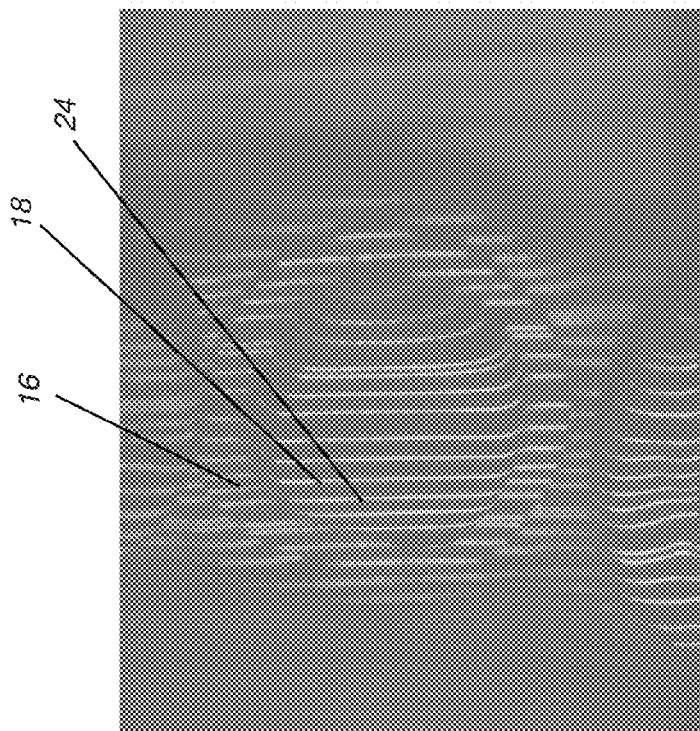


FIG. 2B

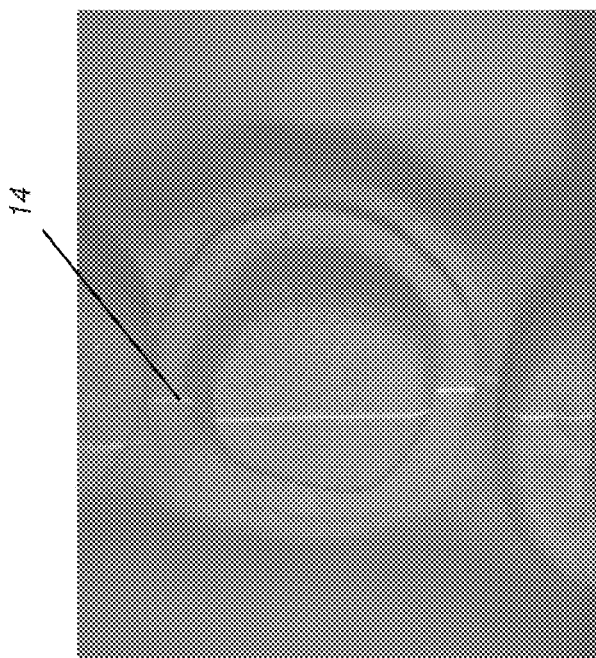


FIG. 2A

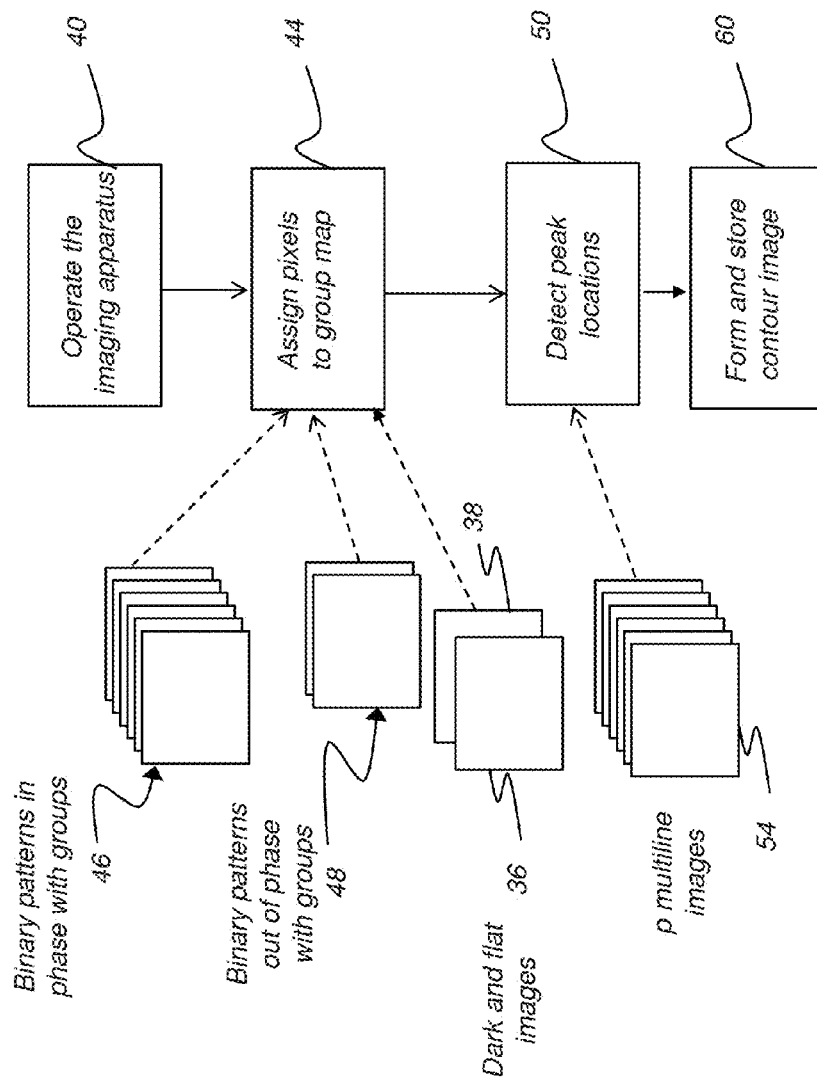


FIG. 3

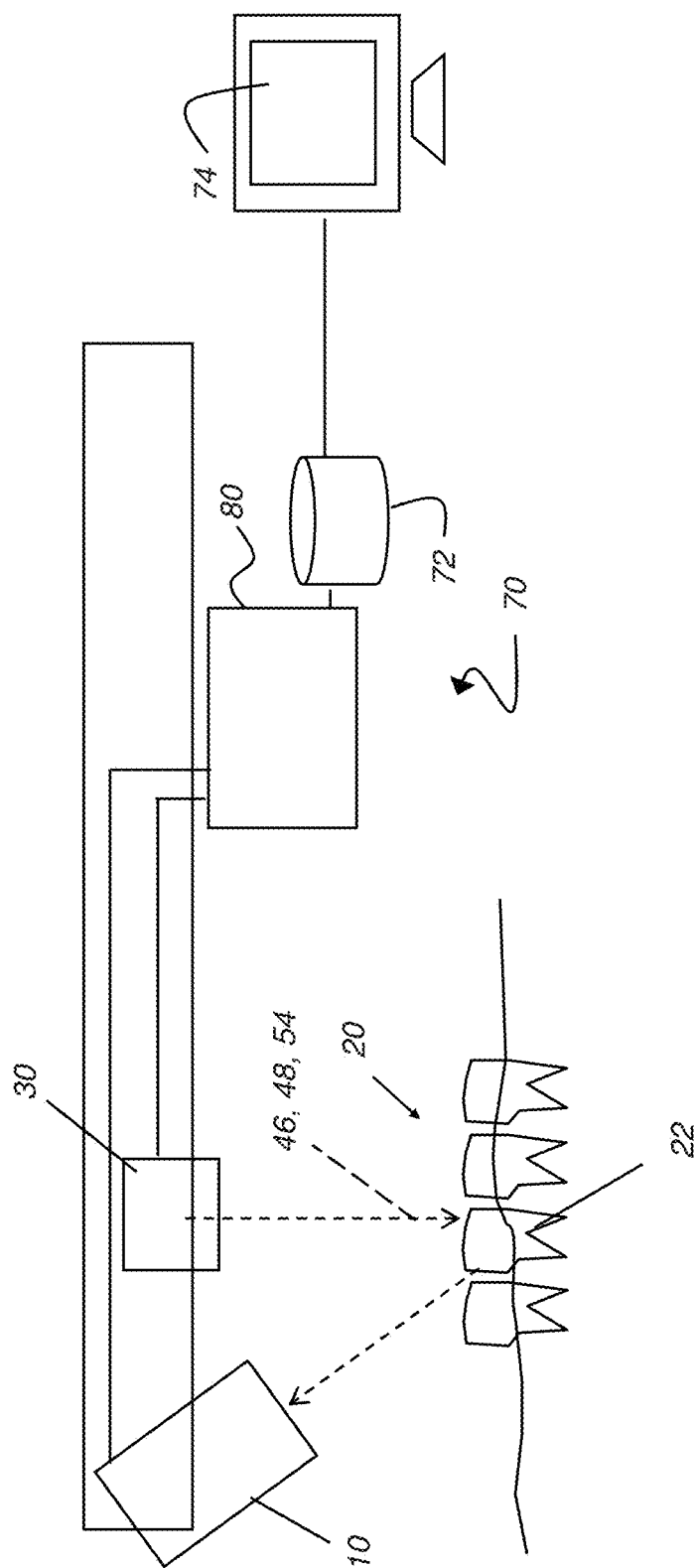


FIG. 4

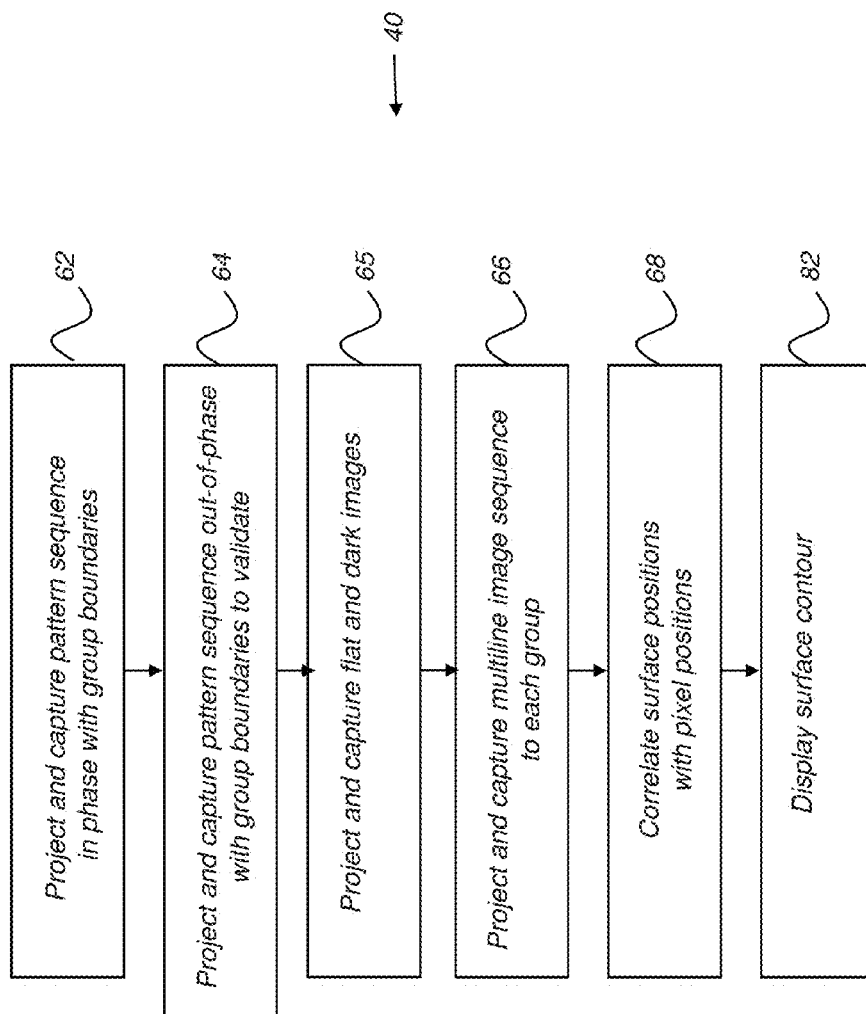


FIG. 5

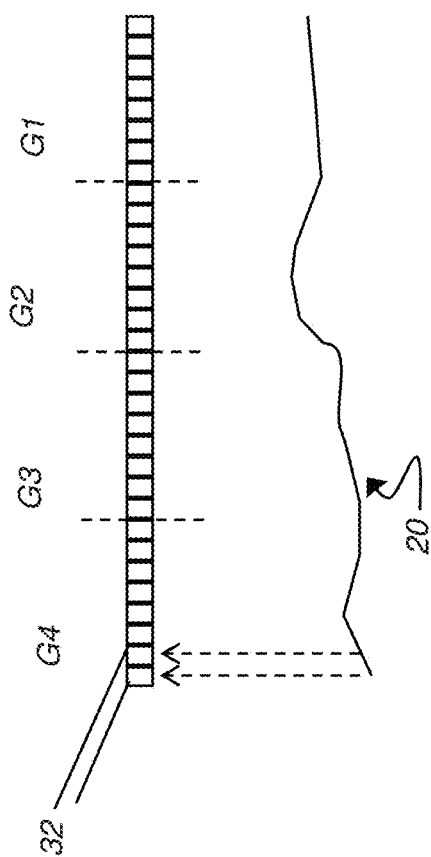


FIG. 6

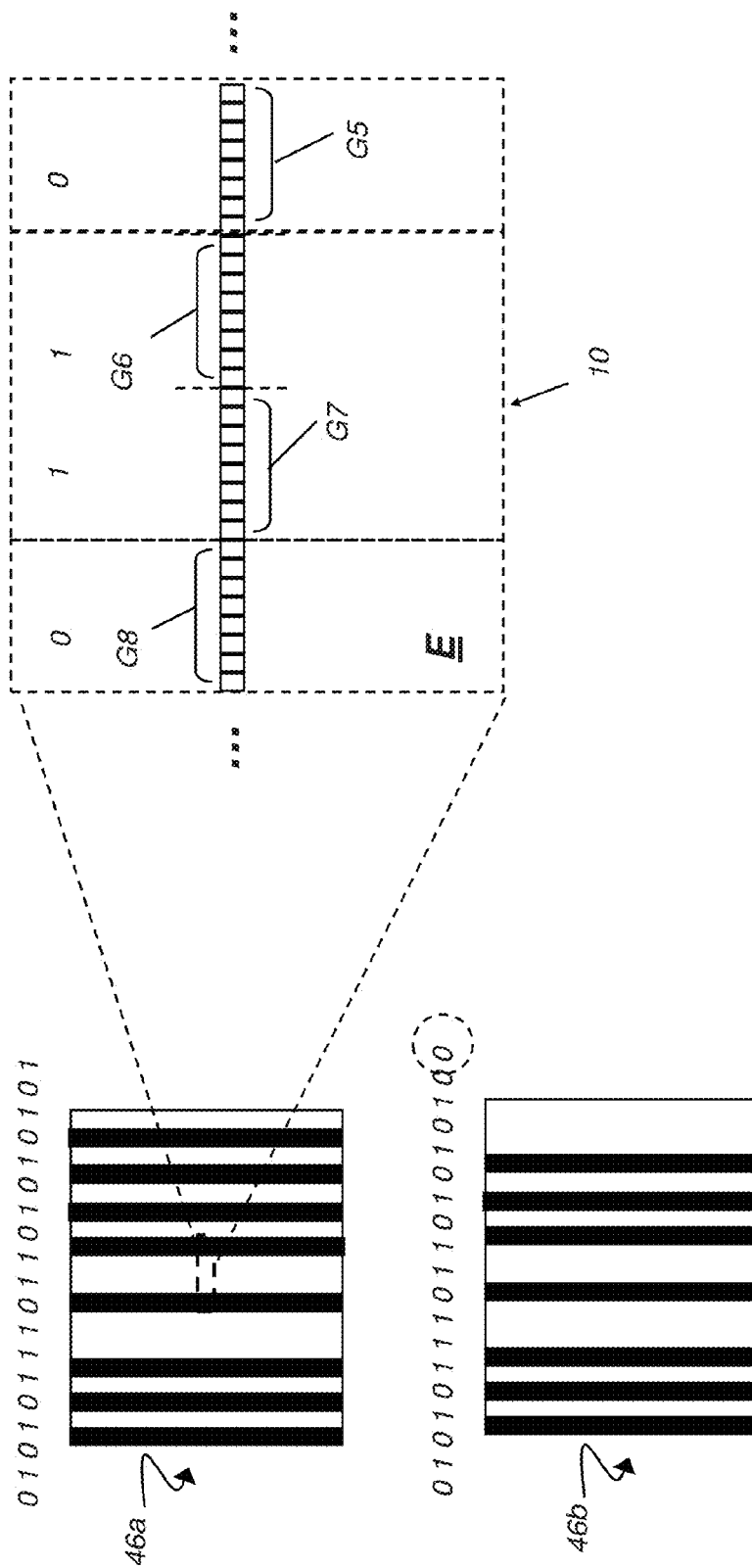


FIG. 7

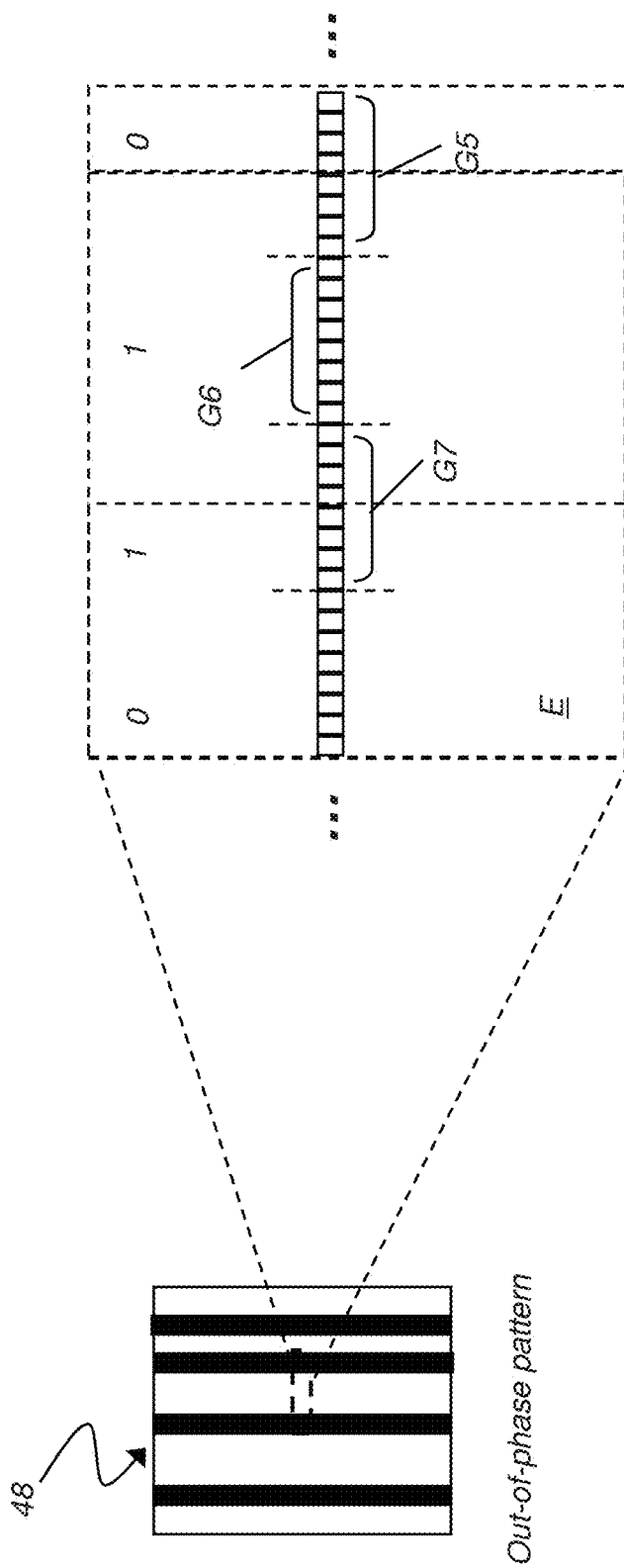


FIG. 8

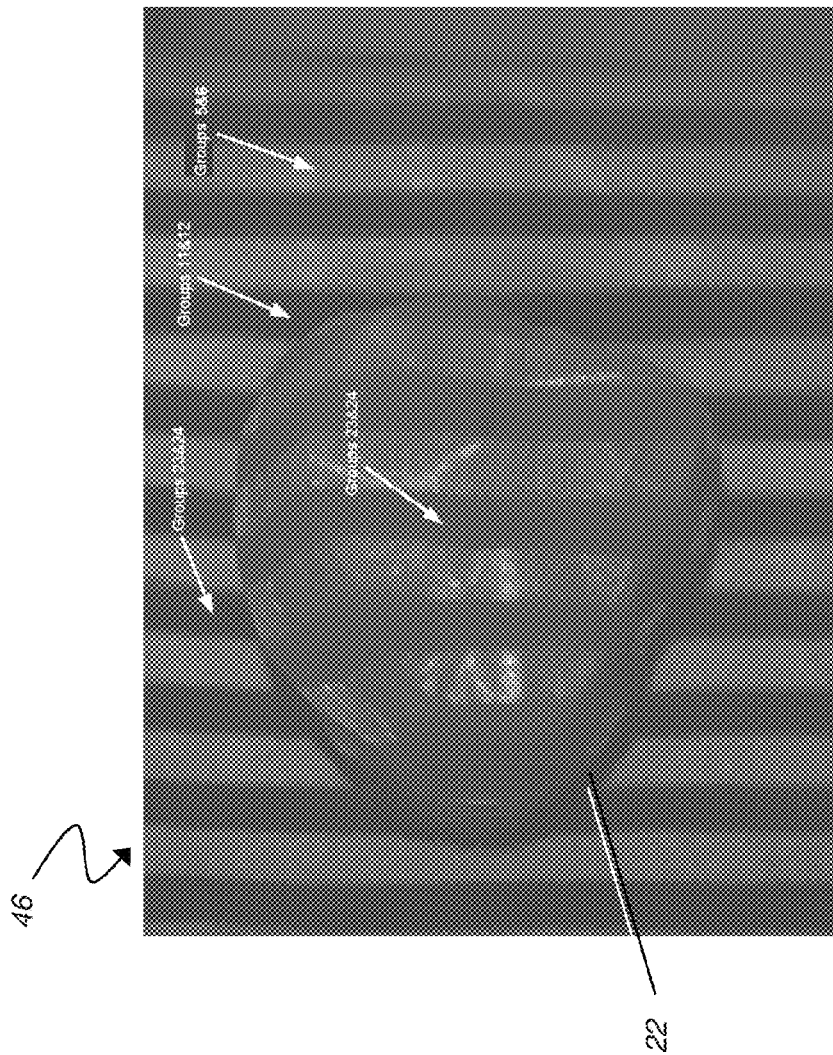


FIG. 9

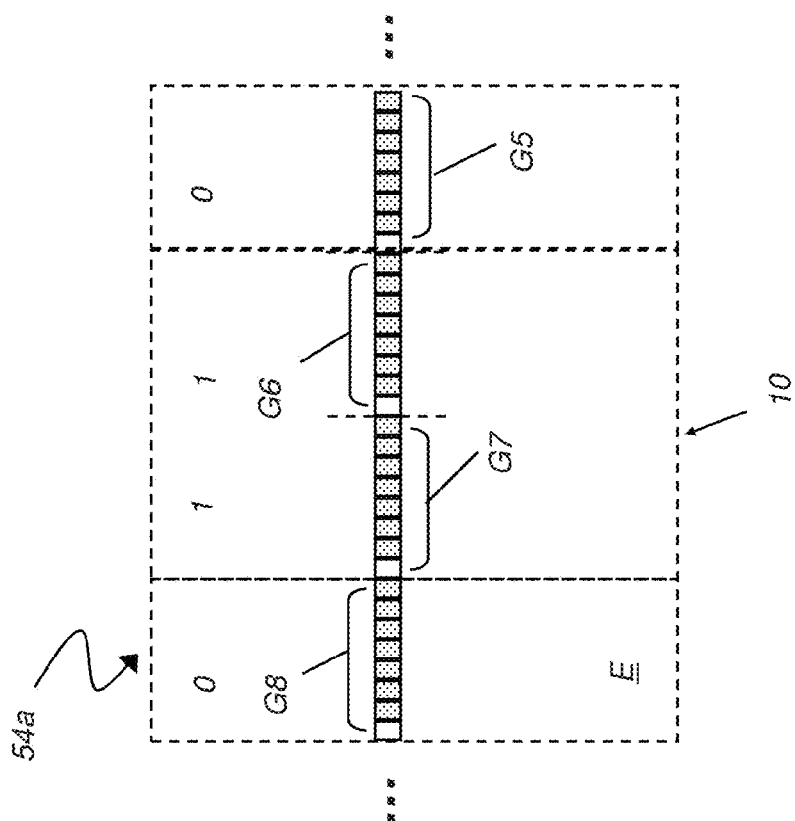


FIG. 10A

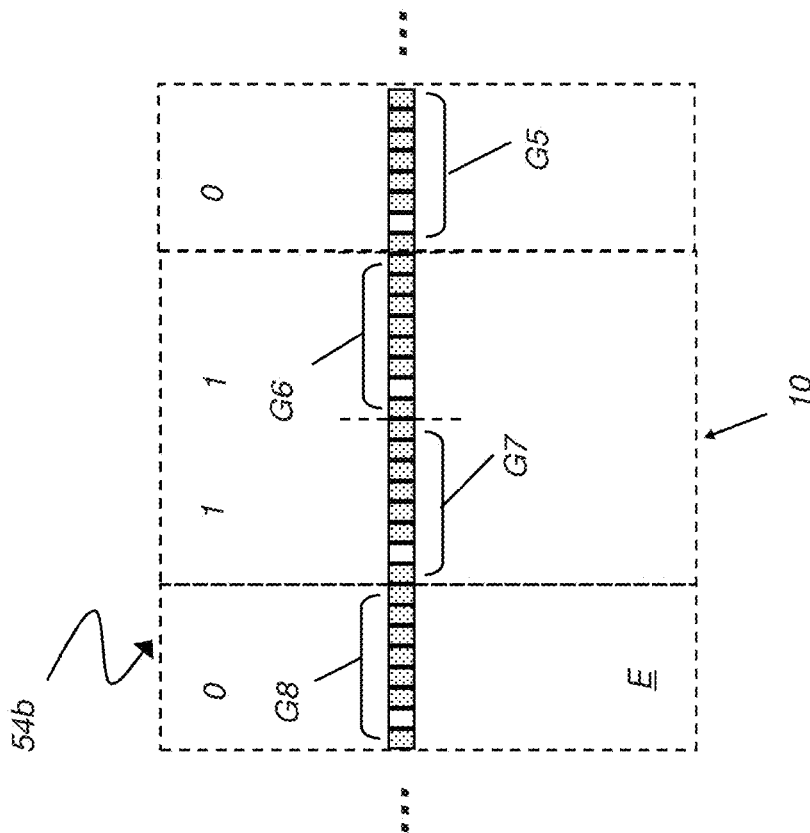


FIG. 10B

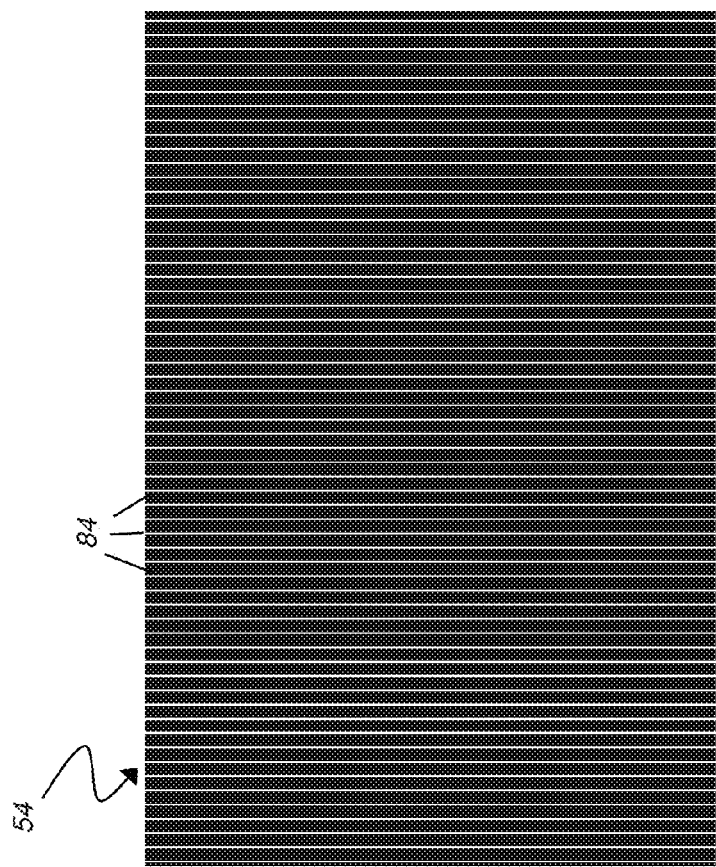


FIG. 11

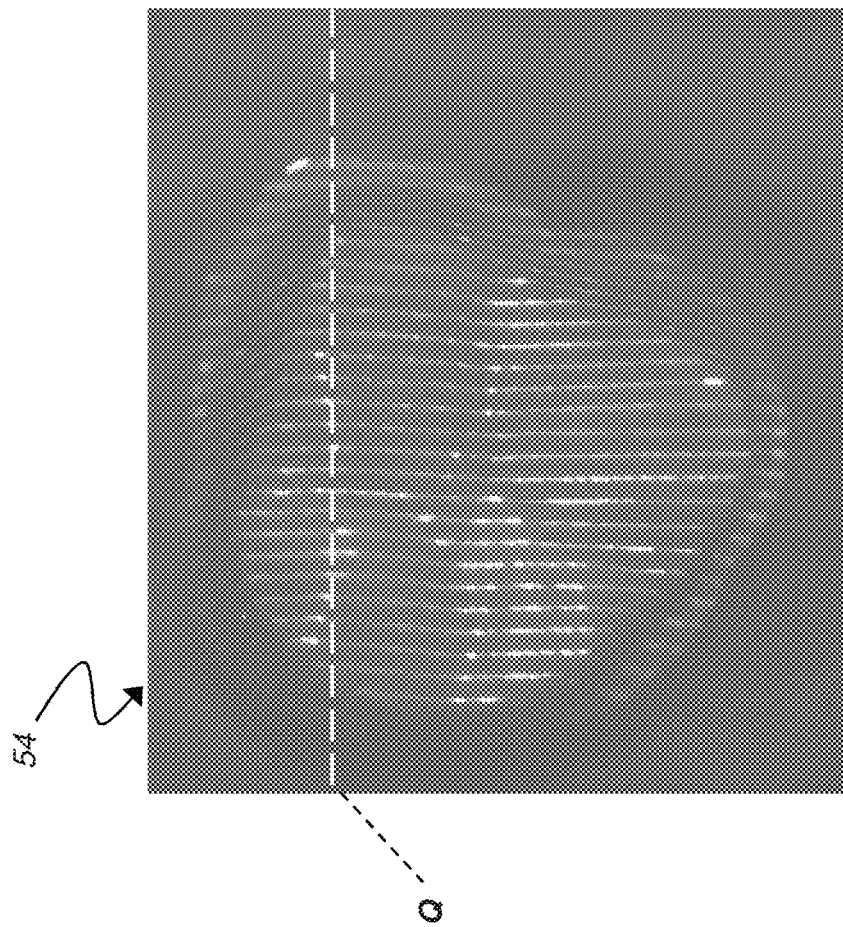


FIG. 12

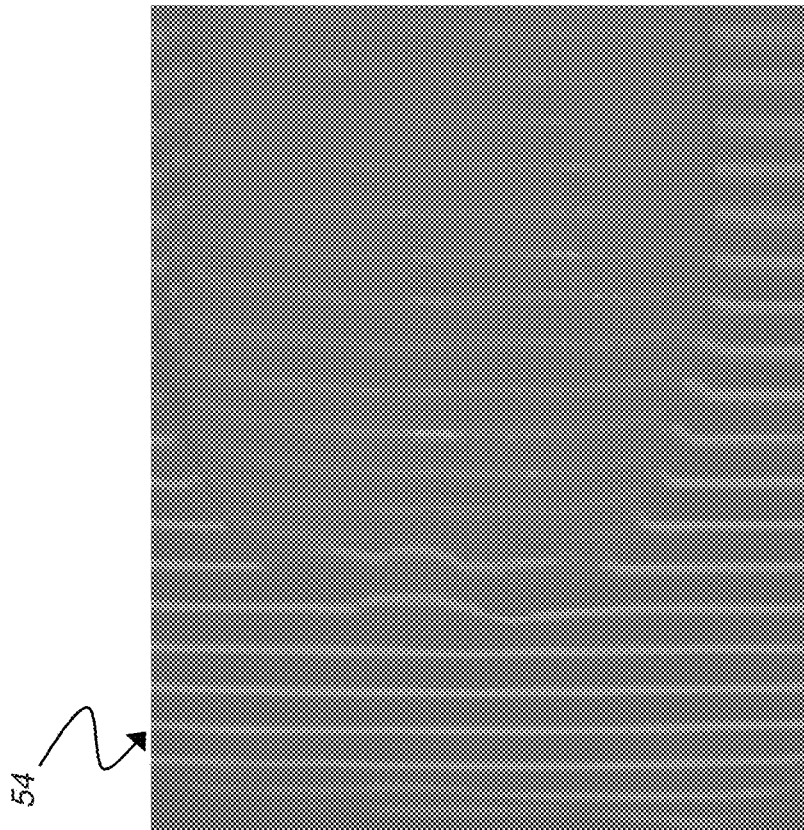


FIG. 13

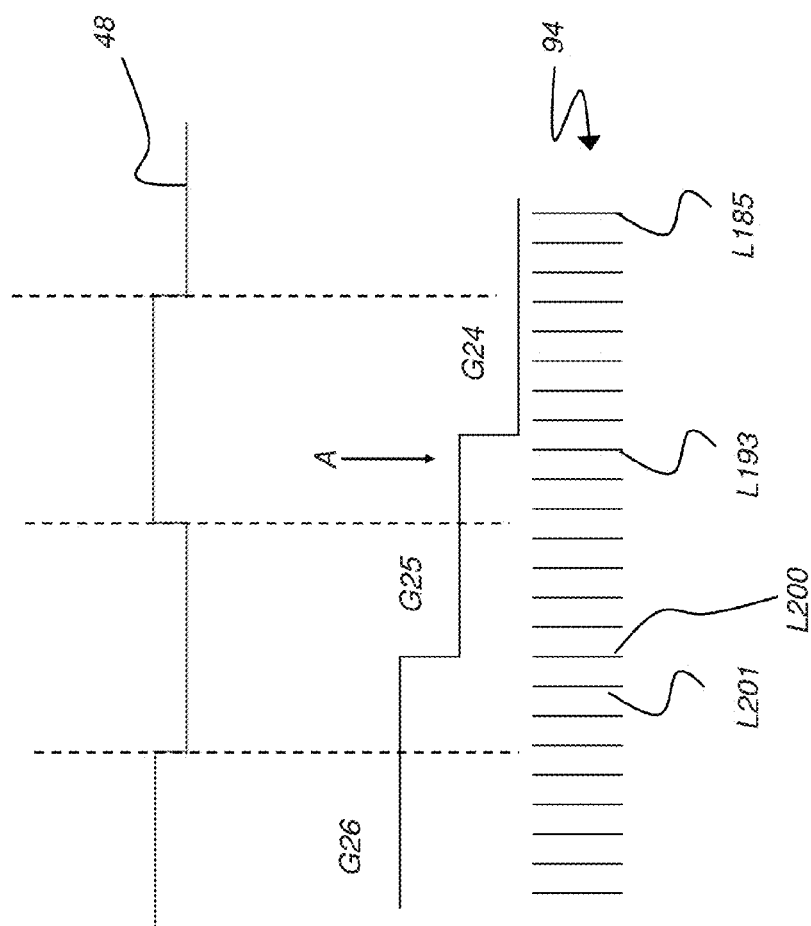


FIG. 14

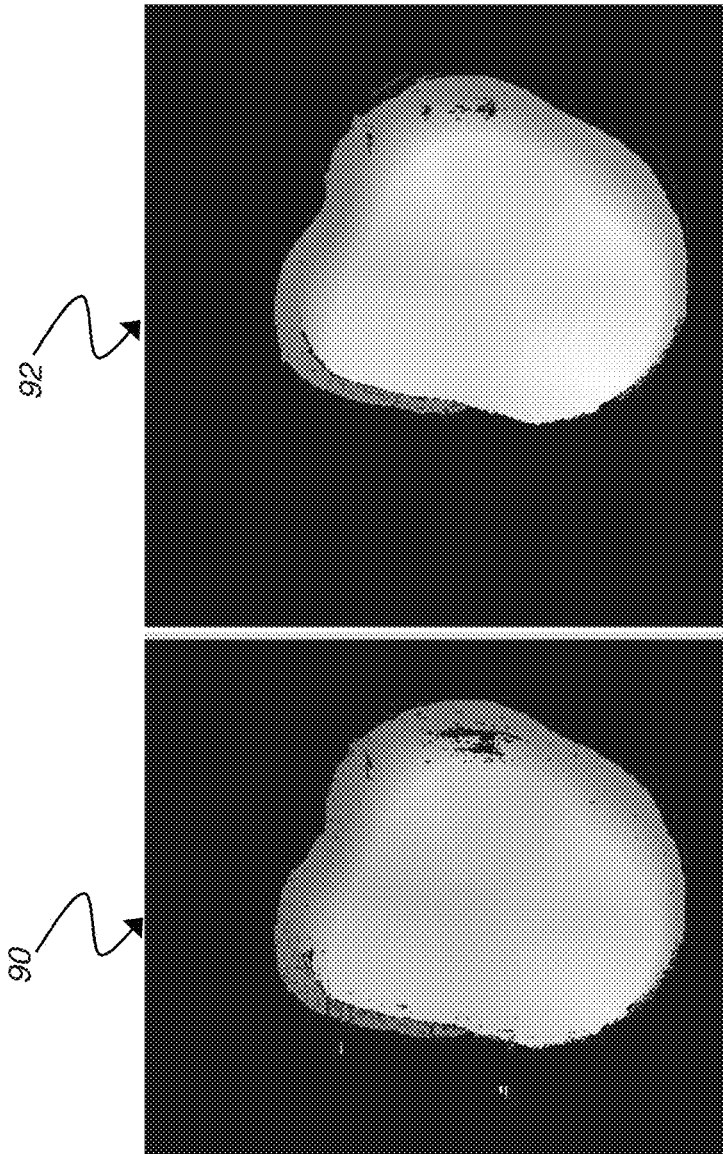
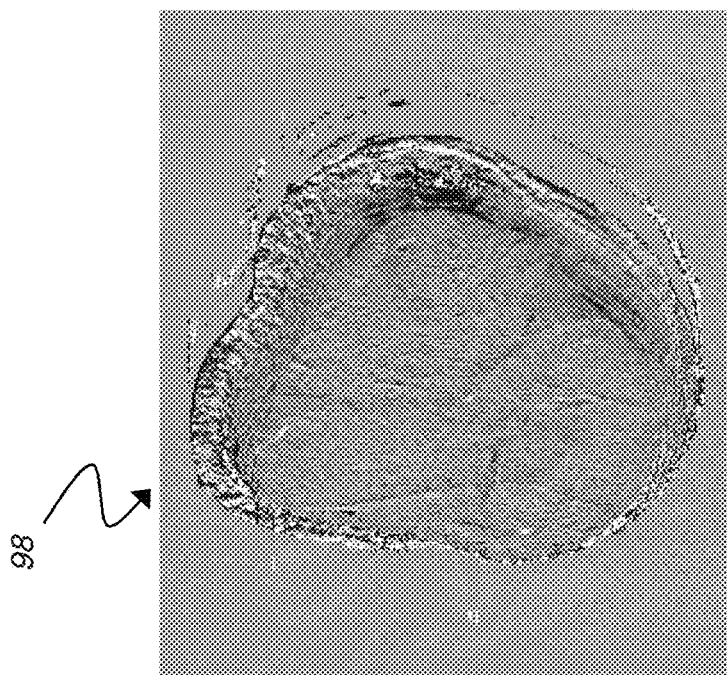


FIG. 15B

FIG. 15A



Difference map

FIG. 16

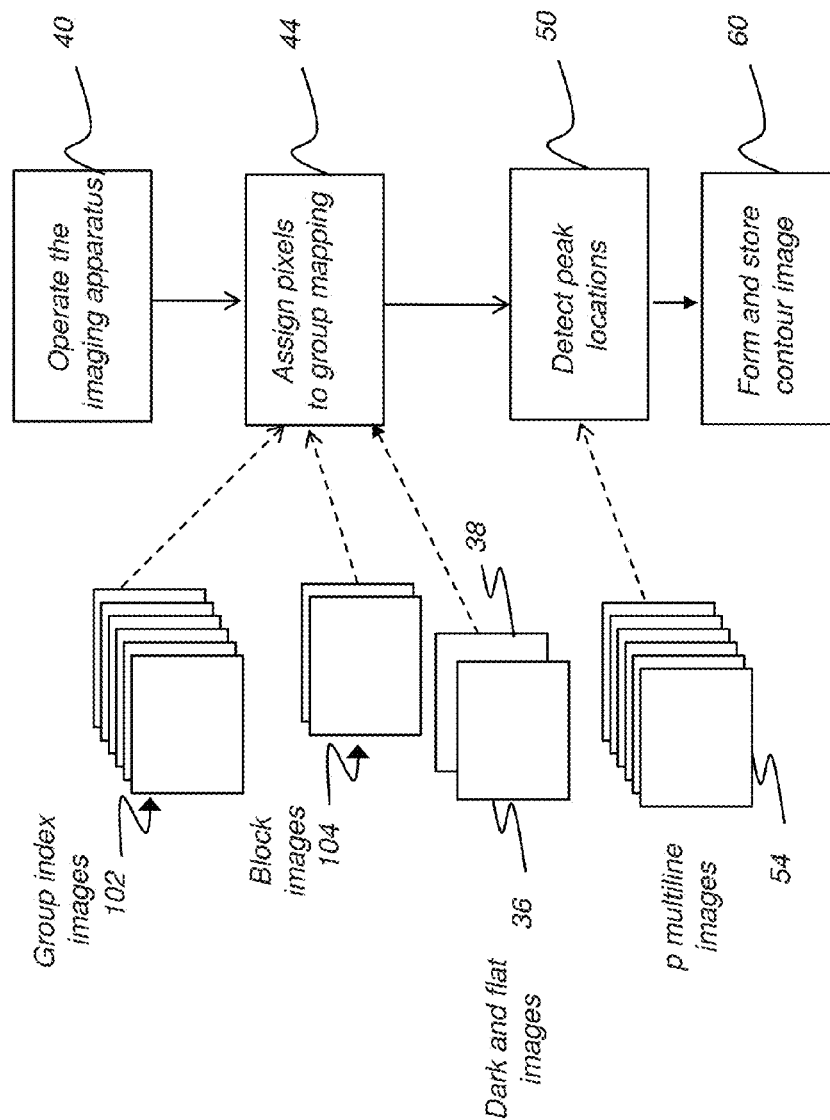


FIG. 17

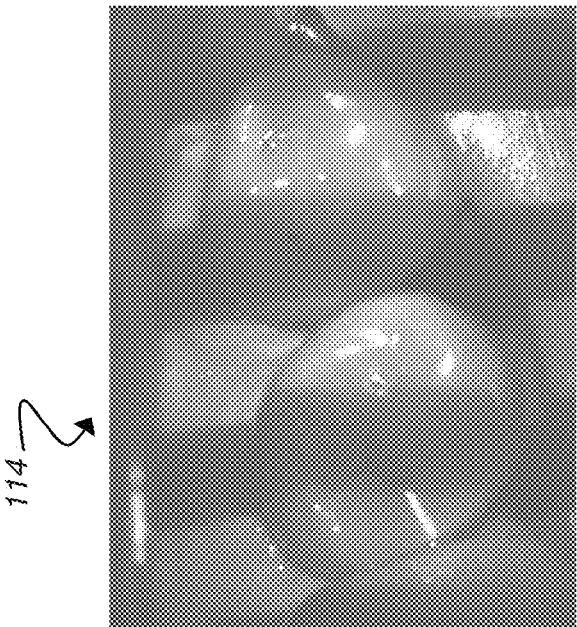


FIG. 18A

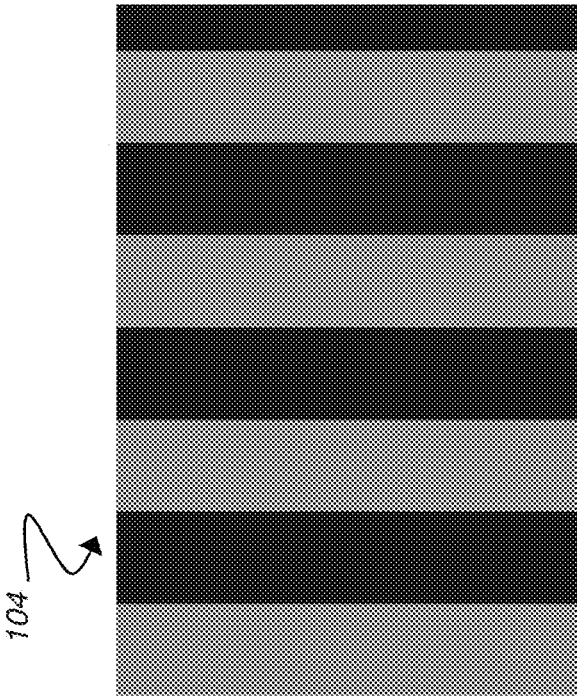


FIG. 18B

112

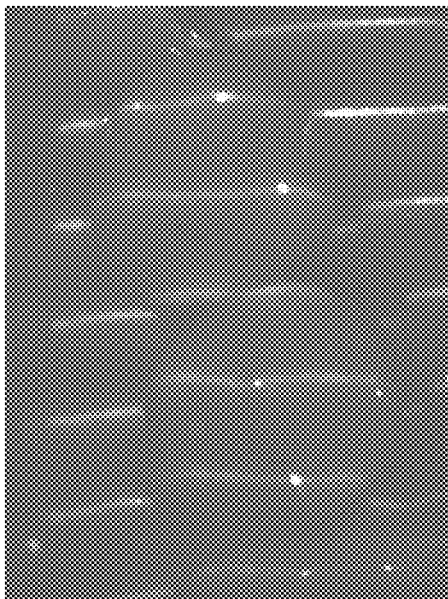


FIG. 19B

102

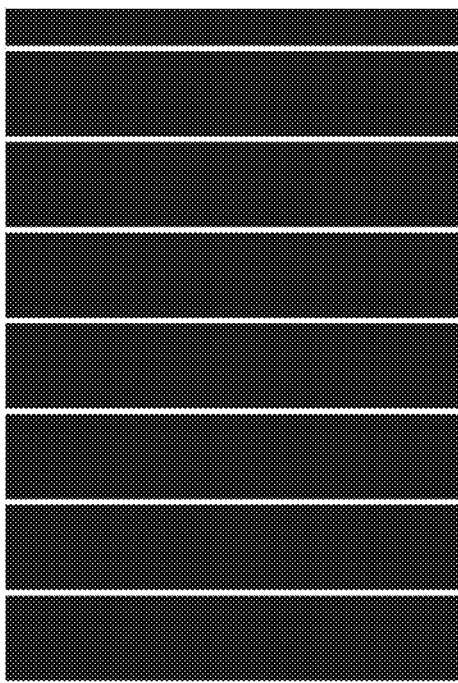


FIG. 19A

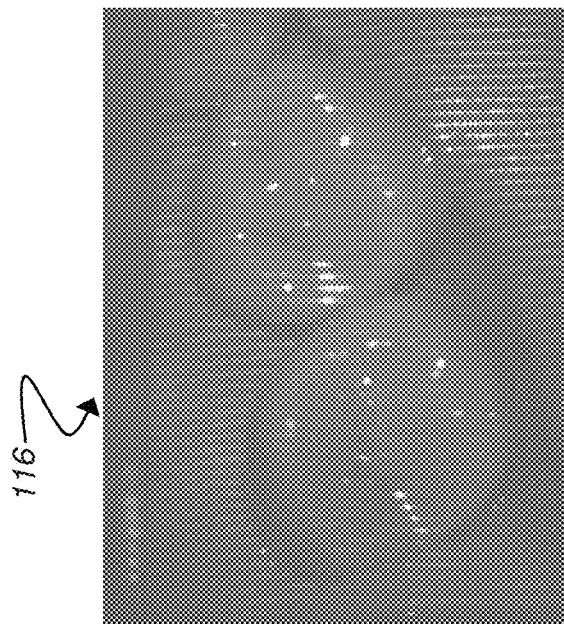


FIG. 20B

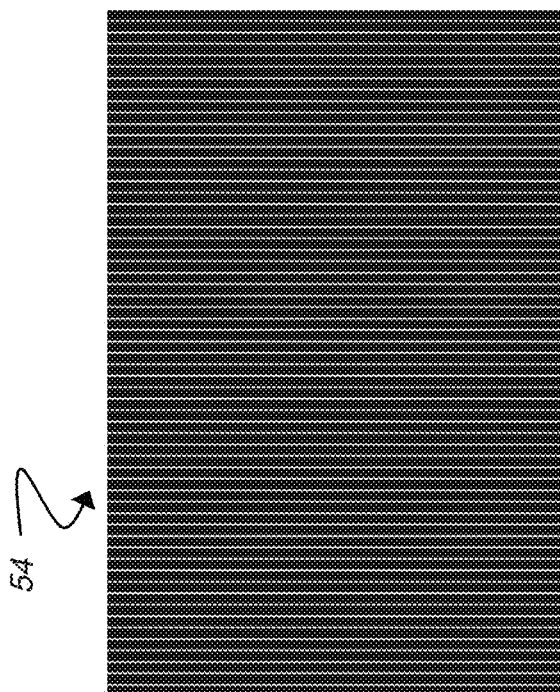


FIG. 20A

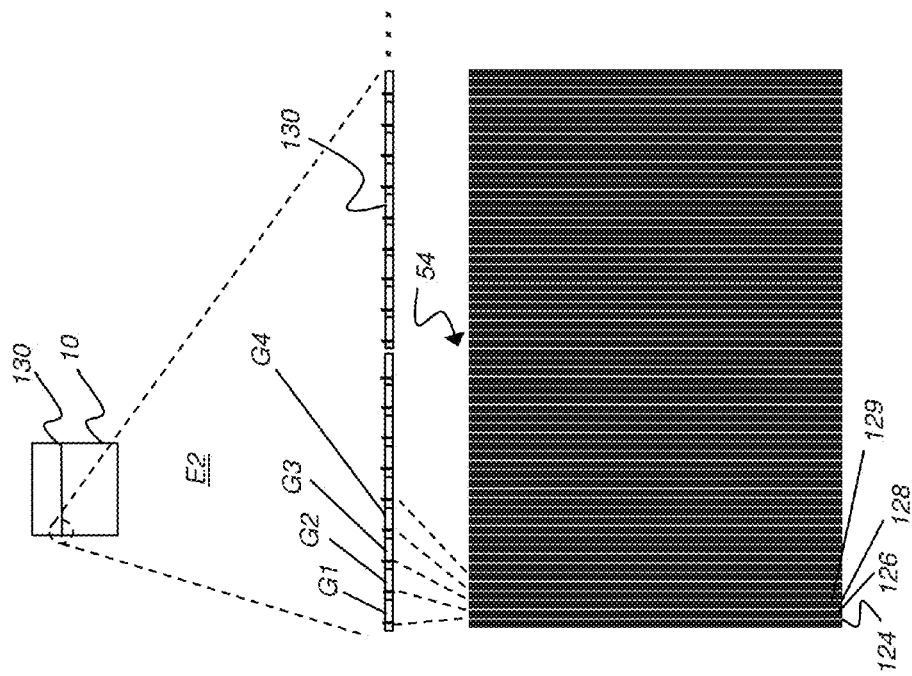


FIG. 21B

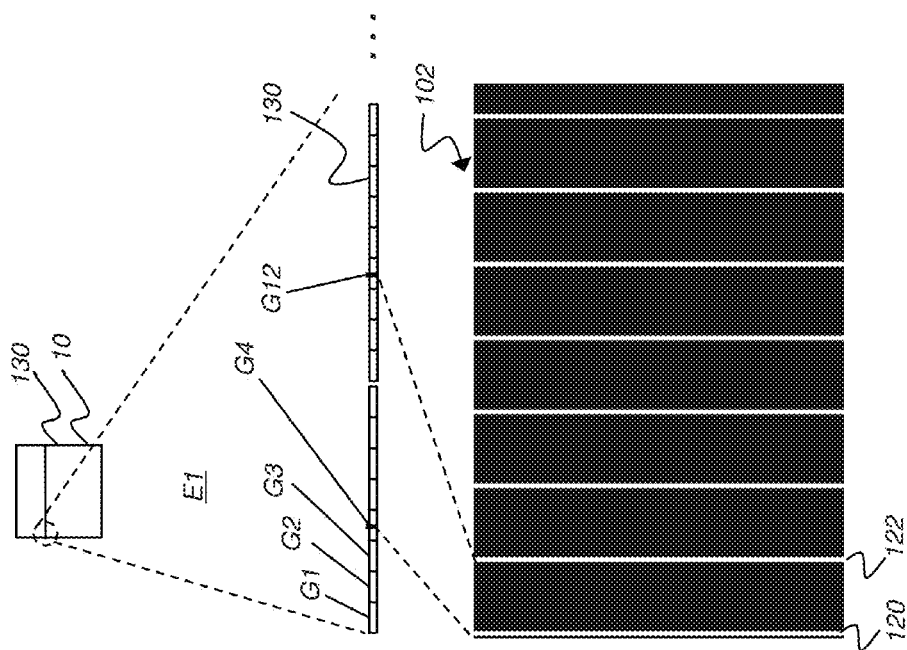


FIG. 21A

FIG. 22A

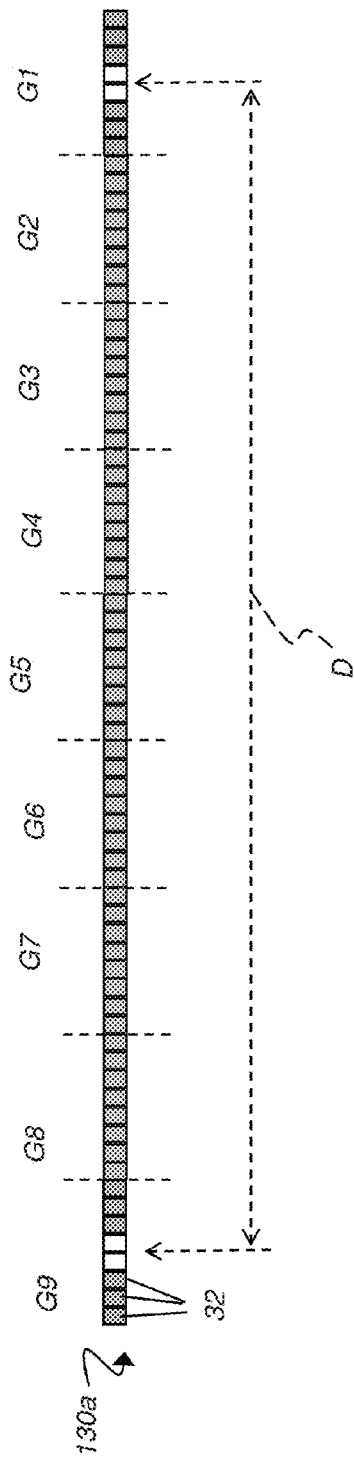
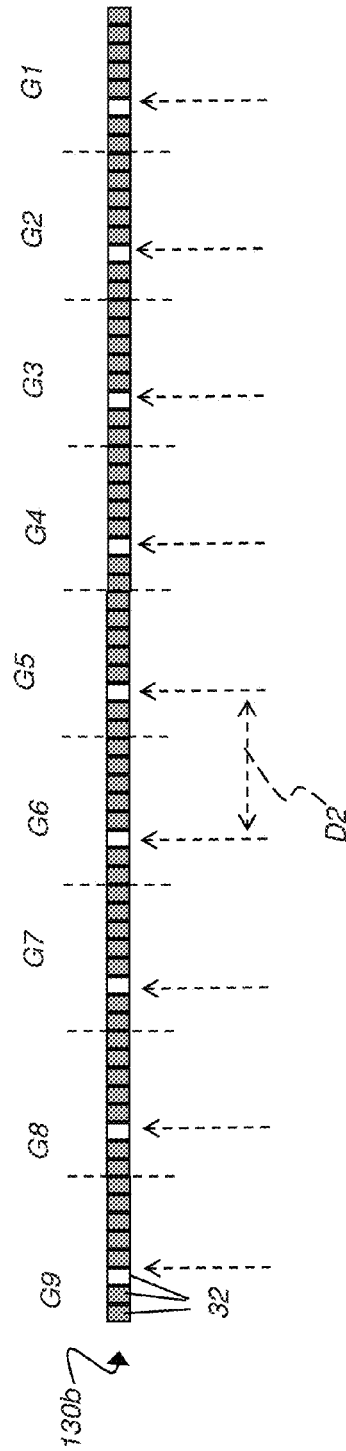


FIG. 22B



1

3D INTRAORAL MEASUREMENTS USING OPTICAL MULTILINE METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a Continuation-in-Part of commonly assigned U.S. Ser. No. 13/293,308, filed 10 Nov. 2011, entitled "3D INTRAORAL MEASUREMENTS USING OPTICAL MULTILINE METHOD" to Milch, incorporated herein in its entirety by reference.

FIELD OF THE INVENTION

The disclosure relates generally to the field of surface shape imaging and more particularly relates to intraoral surface imaging and measurement.

BACKGROUND

Techniques have been developed for obtaining surface contour information from various types of objects in medical, industrial, and other applications. Optical 3-dimensional (3-D) measurement methods provide shape and depth information using images obtained from patterns of light directed onto a surface. Various types of imaging methods generate a series of light patterns and use focus or triangulation to detect changes in surface shape over the illuminated area.

Fringe projection imaging uses patterned or structured light and triangulation to obtain surface contour information for structures of various types. In fringe projection imaging, a pattern of lines of an interference fringe or grating is projected toward the surface of an object from a given angle. The projected pattern from the surface is viewed from another angle as a contour image, taking advantage of triangulation in order to analyze surface information based on the appearance of contour lines. Phase shifting, in which the projected pattern is incrementally spatially shifted for obtaining additional measurements at the new locations, is typically applied as part of fringe projection imaging, used in order to complete the contour mapping of the surface and to increase overall resolution in the contour image.

Fringe projection imaging has been used for surface contour imaging of solid, highly opaque objects and has been used for imaging the surface contours for some portions of the human body and for obtaining detailed data about skin structure. However, a number of technical obstacles have prevented effective use of fringe projection imaging of the tooth. One particular challenge with dental surface imaging relates to tooth translucency. Translucent or semi-translucent materials in general are known to be particularly troublesome for fringe projection imaging. Subsurface scattering in translucent structures can reduce the overall signal-to-noise (S/N) ratio and shift the light intensity, causing inaccurate height data. Another issue relates to high levels of reflection for various tooth surfaces. Highly reflective materials, particularly hollowed reflective structures, can reduce the dynamic range of this type of imaging.

From an optical perspective, the structure of the tooth itself presents a number of additional challenges for fringe projection imaging. Teeth can be wet or dry at different times and along different surfaces and portions of surfaces. Tooth shape is often irregular, with sharp edges. As noted earlier, teeth interact with light in a complex manner. Light penetrating beneath the surface of the tooth tends to undergo scattering within the translucent tooth material. Moreover, reflection

2

from opaque features beneath the tooth surface can occur, adding noise that degrades the sensed signal.

One corrective measure that has been attempted to make fringe projection workable for contour imaging of the tooth is application of a coating that changes the reflective characteristics of the tooth surface itself. A tooth contour imaging system applies a paint or reflective powder to the tooth surface prior to surface contour imaging. For the purposes of fringe projection imaging, this added step enhances the opacity of the tooth and reduces the scattered light effects noted earlier. However, there are drawbacks. The step of applying a coating powder or liquid adds cost and time to the tooth contour imaging process. Because the thickness of the coating layer is often non-uniform over the entire tooth surface, measurement errors readily result. Further, the applied coating, while it facilitates contour imaging, can tend to mask other problems with the tooth and can thus reduce the overall amount of useful information that can be obtained.

Even where a coating or other type of surface conditioning of the tooth is used, however, results can be disappointing due to the pronounced contours of the tooth surface. It can be difficult to provide sufficient amounts of light onto, and sense light reflected back from, all of the tooth surfaces. The different surfaces of the tooth can be oriented at 90 degrees relative to each other, making it difficult to direct enough light for accurately imaging all parts of the tooth.

It can be appreciated that an apparatus and method that provides accurate surface contour imaging of the tooth, without the need for applying an added coating or other conditioning of the tooth surface, would be desirable. Some benefits might include improving the speed, and lowering costs and inconvenience of conventional methods.

SUMMARY

An object of the present invention is to advance the art of surface contour detection of teeth and related intraoral structures. Embodiments of the present invention provide 3-D surface information about a tooth by illuminating the tooth surface with an arrangement of light patterns that help to more closely map pixel locations on a digital imaging array with pixel locations from an illumination device. Advantageously, the present invention can be used with known illumination and imaging component arrangements and is adapted to help reduce ambiguity of sensed patterns when compared against conventional contour detection methods.

These objects are given only by way of illustrative example, and such objects may be exemplary of one or more embodiments of the invention. Other desirable objectives and advantages inherently achieved by the disclosed invention may occur or become apparent to those skilled in the art. The invention is defined by the appended claims.

According to one aspect of the invention, there is provided a method for mapping a sensor pixel array to an illumination pixel array according to a surface, the method executed at least in part on a computer and comprising: forming a group mapping by assigning each pixel in a plurality of pixels on the sensor array to a corresponding group of an ordered set of groups, wherein each group is defined as a set of p adjacent pixels on the illumination pixel array and each ordered set has k groups, by: projecting and recording a sequence of two or more group index images, wherein, with respect to each ordered set of k groups, each projected group index image has, in at least two of the groups, no illuminated pixels and in fewer than $(k-1)$ groups, has from 2 to $(p-1)$ adjacent illuminated pixels, and wherein the sequence of projected group index images uses illuminated pixels from each of the k

3

groups; projecting and recording at least p multiline images onto the surface, wherein each multiline image projects a line within each group; correlating lines in the recorded multiline images with lines in the projected multiline images according to the group mapping; and storing the correlation in a computer-accessible memory, wherein k and p are integers greater than or equal to 3.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features, and advantages of the invention will be apparent from the following more particular description of the embodiments of the invention, as illustrated in the accompanying drawings. The elements of the drawings are not necessarily to scale relative to each other.

FIG. 1 is a schematic diagram that shows mapping a sensor pixel array to an illumination array according to a surface.

FIG. 2A shows illumination of a tooth surface with a single line of light.

FIG. 2B shows illumination of a tooth surface with multiple lines of light.

FIG. 3 is a logic flow diagram that shows a sequence for obtaining surface contour image data according to an embodiment of the present invention.

FIG. 4 is a schematic diagram showing an imaging apparatus.

FIG. 5 is a logic flow diagram that shows an image projection and recording sequence.

FIG. 6 is a schematic diagram that shows part of a row of pixels on the imaging sensor array.

FIG. 7 is a schematic diagram that shows in-phase binary projected patterns for group mapping.

FIG. 8 is a schematic diagram that shows a binary projected pattern of a second out-of-phase set.

FIG. 9 shows a single projected binary pattern.

FIG. 10A shows a portion of the illumination array for forming a multiline image.

FIG. 10B shows another portion of the illumination array for forming a multiline image.

FIG. 11 is a plan view of an exemplary multiline image.

FIG. 12 is a plan view of a projected multiline image on a tooth.

FIG. 13 is another plan view of a projected multiline image on a tooth.

FIG. 14 is a schematic diagram showing how data from binary pattern images and multiline images are combined.

FIGS. 15A and 15B compare results for uncoated and coated teeth.

FIG. 16 is a difference map combining the results of FIGS. 15A and 15B.

FIG. 17 is a logic flow diagram that shows steps for forming a contour image according to an embodiment of the present invention.

FIG. 18A shows the illumination pattern that is projected in an optional block image.

FIG. 18B shows a tooth image obtained using the illumination pattern of FIG. 18A.

FIG. 19A shows the illumination pattern that is projected in a group index image.

FIG. 19B shows a tooth image obtained using the illumination pattern of FIG. 19A.

FIG. 20A shows the illumination pattern that is projected in a multiline image.

FIG. 20B shows a tooth image obtained using the illumination pattern of FIG. 20A.

4

FIG. 21A is a schematic image showing how an index image is formed according to an embodiment of the present invention.

FIG. 21B is a schematic image showing how a multiline image is formed.

FIGS. 22A and 22B are schematic diagrams that compares pixel illumination patterns for group index and multiline images.

DETAILED DESCRIPTION

This application is a Continuation-in-Part of commonly assigned U.S. Ser. No. 13/293,308, filed 10 Nov. 2011, entitled "3D INTRAORAL MEASUREMENTS USING OPTICAL MULTILINE METHOD" to Milch, incorporated herein in its entirety by reference.

The following is a detailed description of the preferred embodiments of the invention, reference being made to the drawings in which the same reference numerals identify the same elements of structure in each of the several figures. Where they are used, the terms "first", "second", and so on, do not necessarily denote any ordinal, sequential, or priority relation, but are simply used to more clearly distinguish one element or set of elements from another.

The schematic diagram of FIG. 1 shows, with the example of a single line of light L , how patterned light is used for obtaining surface contour information. A mapping is obtained as an illumination array 10 directs a pattern of light onto a surface 20 and a corresponding image of a line L' is formed on an imaging sensor array 30 . Each pixel 32 on imaging sensor array 32 maps to a corresponding pixel 12 on illumination array 10 according to modulation by surface 20 . Shifts in pixel position, as represented in FIG. 1, yield useful information about the contour of surface 20 . It can be appreciated that the basic pattern shown in FIG. 1 can be implemented in a number of ways, using a variety of illumination sources and sequences and using one or more different types of sensor arrays 30 . Illumination array 10 can utilize any of a number of types of arrays used for light modulation, such as a liquid crystal array or digital micromirror array, such as that provided using the Digital Light Processor or DLP device from Texas Instruments, Dallas, Tex. This type of spatial light modulator is used in the illumination path to change the light pattern as needed for the mapping sequence.

FIGS. 2A and 2B show aspects of one problem with conventional approaches for using patterned light to obtain surface structure information from the human tooth. FIG. 2A shows illumination with a single line of light 14 onto the tooth, with pronounced shifting of the illumination at the tooth edges. Projection of a single line in this manner, scanned across the tooth and imaged at numerous points during the scan, can provide accurate information about portions of the surface area; however, some information is lost even with this method, such as where line segments are separated from each other. FIG. 2B shows surface imaging using a pattern with multiple lines of light. Where there are abrupt transitions along the surface, it can be difficult to positively identify the segments that correspond to each projected line and mismatches can easily occur, leading to inaccurate conclusions about surface characteristics. For example, it can be difficult to determine whether line segment 16 is from the same line of illumination as line segment 18 or adjacent line segment 24 .

Embodiments of the present invention address the problem of surface contour mapping using a sequence of projected images that help to better correlate pixels on the imaging sensor array with projected lines from the illumination array.

5

To do this, embodiments of the present invention use an arrangement of binary images to group pixels on the imaging sensor array with corresponding pixels on the illumination pixel array. A group mapping is formed by assigning pixels on the sensor array to an ordered set of groups, each group having a fixed number of pixels. The group mapping can be stored as a particular data structure or may be otherwise represented in data that relates each pixel to a particular group structure, using mapping techniques well known to those skilled in the data representation arts. In the context of the present disclosure, the terms “group map” and “group mapping” are considered to be equivalent, since the relationship of pixels and groups can be represented and stored in any of a number of ways.

Referring to the flow diagram of FIG. 3, there is shown a sequence of image projection, detection, and processing steps used for surface contour detection and executed at least in part on a computer according to an embodiment of the present invention. In an image capture step 40, the operator positions the imaging apparatus and captures a series of images, as described subsequently. The images consist of a number n of binary patterns 46 and m binary patterns 48 and p multiline images 54 and can be captured in any order. Once the images are captured, a pixel assignment step 44 executes, in which pixels on the image sensor array are assigned to a group map or mapping that corresponds to pixels on the illumination array. Images for the group mapping are from binary patterns 46 and 48, described in more detail subsequently. An additional dark image 36, with no illumination, and flat image 38 with full frame illumination are also obtained to help in signal processing, as described subsequently.

Continuing with the sequence of FIG. 3, a set of p multiline images 54 is also obtained, from which peak locations, that is, locations of highest intensity, can be detected in a location detection step 50. A mapping step 60 then forms and stores the contour image in a memory, such as in a temporary display memory that is associated with a display monitor, for example.

Relative to FIG. 1, a binary pattern has one or more bright bands that are two or more pixels wide on illumination array 10. A multiline image has one or more bright bands that are one pixel wide on illumination array 10. The multiline image has at least one bright-to-dark or dark-to-bright transition within each group of pixels.

The schematic diagram of FIG. 4 shows an imaging apparatus 70 for projecting and imaging the binary patterns 46 and 48 and multiline images 54. A control logic processor 80, or other type of computer controls the operation of illumination array 10 and imaging sensor array 30. Image data from surface 20, such as from a tooth 22, is obtained from imaging sensor array 30 and stored in a memory 72. Control logic processor 80 processes the received image data and stores the mapping in memory 72. The resulting image from memory 72 is then optionally displayed on a display 74. Memory 72 may also include a display buffer.

The logic flow diagram of FIG. 5 shows the image projection and capture sequence described as image capture step 40 in FIG. 3 and using the imaging apparatus 70 of FIG. 4 in more detail. A first binary pattern recording step 62 records at least n images from a first set of n binary patterns projected onto the surface, in which transitions between pixels occur only at group boundaries, as described subsequently. This set of n images is described as being “in-phase” with the group arrangement. A second binary pattern recording step 64 then records m binary patterns projected onto the surface, in which one or more transitions between pixels in each of the m patterns are offset from group boundaries, again described in

6

more detail subsequently. This set of m images is described as being “out-of-phase” with the group arrangement, with at least one transition within a group. A dark and flat image recording step 65 then records dark field and flat field images.

The combination of images recorded from recording steps 62, 64, and 65 are then used for forming the group map in pixel assignment step 44 of FIG. 3. A multiline image recording step 66 projects onto the surface and records at least p multiline images, as described in more detail subsequently. Following image capture, a correlation step 68 then correlates surface positions with pixel positions on image sensor array 30 as part of mapping step 60 in FIG. 3. An optional display step 82 then displays the surface contour obtained from the mapping.

15 Forming the Group Mapping

Schematic diagrams of FIGS. 6, 7, and 8 show various aspects of the process for forming the group map according to an embodiment of the present invention. FIG. 6 shows part of a row of pixels 32 on imaging sensor array 30 corresponding to positions on surface 20. Each group has a predetermined number p of adjacent pixels 32, with eight pixels 32 per group in the example mapping that is shown. Vertical dashed lines in FIGS. 6-8 indicate group boundaries. At a group boundary, wherein each group has p pixels numbered from 0, 1, 2, . . . ($p-1$), the ($p-1$)th pixel of one group is adjacent to the 0th pixel of the next, or adjacent, group in the row; the space between these two adjacent pixels, with one pixel in each of two adjacent groups, defines a group boundary. The group boundary is considered to be “shared” by two adjacent groups. Two sequences of projected binary patterns are used to establish the group map. The schematic diagram of FIG. 7 shows the first pattern. Here, n images from a set of n binary patterns are projected from illumination array 10 in which each row is arranged according to groups. Representative eight-pixel groups G8, G7, G6, and G5 are shown, numbered in descending order from right to left in this example. Two of the n binary patterns 46a and 46b are shown, with binary 1, 0 representation shown for respective dark (off or 0)/bright (on or 1) bands that have transitions from bright to dark or, alternately, from dark to bright, at group boundaries. In the example shown at enlarged portion E, a 0110 portion of the binary pattern 46a is represented, with transitions between 0 and 1 occurring only at group boundaries. Binary pattern 46b is the next binary pattern in sequence, changing only one bit from the binary pattern at 46a. Consistent with an embodiment of the present invention, the successive binary patterns are arranged in a sequence that emulates a Gray code, in which each successive pattern (x) changes by only one bit from the previous pattern ($x-1$). This use of a Gray code emulation is advantaged for helping to reduce ambiguity in determining which corresponding pixel on imaging sensor array 30 maps to a group defined on illumination array 10 (FIG. 1). Bright bands in the binary patterns 46a and 46b, corresponding with binary number 1 in FIGS. 7 and 8, have a width that is in integer increments of a group of pixels, so that a bright band will be as wide as one, two, or more than two groups of pixels from the illuminator array. In the example of FIG. 7, in which a group has 8 pixels, a bright band in the binary pattern 46a or 46b is 8, 16, 24, 32, or some other integer multiple of 8 pixels wide.

The schematic diagram of FIG. 8 shows projection of one of the second set of m binary patterns 48. Here, one or more of the binary 0/1 or 1/0 transitions between pixels are offset from group boundaries. In the example shown, group G7 spans across the corresponding transition that is offset from its boundary with group G6. Similarly, a transition is offset from the border of group G5, splitting pixels in this group into

those on one side of the transition and those on the other. This use of an offset or out-of-phase pattern is a feature of embodiments of the present invention and acts as a further check on group boundaries, to help resolve possible ambiguity between group assignments. FIG. 9 shows a single projected binary pattern **46** relative to a typical tooth.

Consistent with an embodiment of the present invention, an analog filter is applied to each of the binary pattern images. This has been found to be of value in areas of low signal content. Alternately, thresholding using a digital filter can be employed for this purpose.

There is some level of signal (a "cut-off point") in the flat image **38** (FIG. 3) that can be too low for accurate comparisons. This level can simply be set as a parameter for the processing software. It can also be calculated adaptively by finding all the peaks in the multiline image, as described subsequently, and noting the "flat" values at those peak positions. Pixels with levels below this cutoff point are simply declared to be indeterminate, having unknown states, and are not processed further.

After thresholding, the n block images are combined at each pixel to form an n -bit number. This number is then translated through the inverse of an encoding table to identify the corresponding group number. In the absence of errors, this completes the block image processing.

Geometrically, when moving from one side of the image to the other along a row, the group number must change monotonically. (The numbers on different rows may not align, but within each row, they are monotonic.) This makes it possible to 'proofread' the group numbers on each row, discarding places where noise has disturbed the expected monotonic increase of group number.

Multiline Images

As was noted with respect to the sequences shown in FIGS. 3 and 5, a set of at least p multiline images is projected onto the surface, in addition to the n in-phase and m out-of-phase images. The schematic diagram of FIG. 10A shows, for a single row of illumination array **10**, a portion of a first multiline image **54a** in which the left-most pixel in each group is illuminated to form a line. FIG. 10B shows another multiline image **54b** in which the next pixel in each group is illuminated. Where each group has 8 pixels, as in the examples shown herein, this sequence repeats so that there are at least 8 multiline images, one for each pixel in each group. Transitions from dark to light or from light to dark are only with respect to a single pixel width in a multiline image; each bright band of light that forms a line is a single pixel wide. Each multiline image projects a single line within each group, so that there is at least one bright-to-dark or dark-to-bright transition between adjacent group boundaries in a multiline image. In general, where each group has a number p adjacent pixels, at least p multiline images are projected onto the surface and recorded. In addition, more than 8 multiline images can be projected and recorded, in cyclical or other sequencing arrangement. FIG. 11 shows a multiline image **54** with a line **84** within each group as projected from illumination array **10**. FIGS. 12 and 13 show exemplary multiline images **54** as projected onto the surface **20** and recorded by imaging sensor array **30**. The dashed line **Q** in FIG. 12 indicates one row of pixels on imaging sensor array **30**.

Consistent with an embodiment of the present invention, each of the multiline images is analyzed as a set of independent rows, to locate each intensity peak in the row. This is done in two steps. Initially, a combination of smoothing filter and differentiating filter locates pixels where there is a peak signal. Then, a parabola is fit to the observed points around the identified pixel in order to locate the peak with sub-pixel

accuracy. The background around the peak is also estimated to provide additional information on relative peak height. A candidate peak can be dropped from the list of peaks if it is too weak or too close to another peak. The result of the analysis is a long peak list (30,000 to 100,000 for a typical imaging sensor array) of precise locations where intensity peaks were observed.

Combining the Group Map and Peak List

In the absence of noise or errors, combination of group and peak data is driven by the list of peaks, which contains the peak location in x and y (i.e. pixel location along the row and the row number), the peak height, the peak width, and the image from which it came (multiline images 1 to p). For each peak, the group number from the nearest pixel in the Group Map is retrieved. The group number and image number are combined to calculate the line on the illuminator, 1 to 480 in a 480 line image. This gives three essential "pixel positions" for the peak: the x and y location on the imager and the x location on the illuminator, just as would be obtained from a single projected point.

Next, an approximate position of the point on the tooth or other surface is calculated, using the three pixel positions and calibration parameters. These approximate positions are processed, using information known from calibration, to determine an accurate location (x , y , z) on the surface. All of these locations form the point cloud, which is the final output of the combination algorithm.

The in-phase binary patterns **46** and out-of-phase binary patterns **48** are combined to improve the accuracy of the mapping and to compensate and identify various physical effects that might otherwise induce errors in the Group Map. For the explanation that follows:

(1) the term "phase" relates to the image number (1- p) from which a peak came;

(2) the numerical labeling of illuminator lines is assumed to increase from right to left on the imaging sensor array; a monotonic rule states that the group number must increase from right to left along a row; and

(3) there are assumed to be multiple (at least 2 or 3) imaging sensor array pixels for every illuminator array pixel.

Referring to the schematic diagram of FIG. 14, a portion of an out-of-phase binary pattern **48** is shown, with corresponding lines from a first captured image frame from the multiline images represented. A number of representative lines L185, L193, L200, and L201 are shown. A portion of the group mapping is also shown for groups G24, G25, and G26. Corresponding illuminator array pixel center positions **94** are also shown.

Lines L193 to L200 are in group G25. The out-of-phase binary pattern **48** changes between groups, as described previously. An arrow **A** marks a peak observed in a phase 1 multiline image. (The phase numbers count from right to left in this example arrangement.) Errant group codes can be detected in a number of ways, including the following:

(i) The group code should change only near phases 1 and 8. For peaks in phases 2-7, all the pixels around a peak center should have the same group code.

(ii) Assume there is a peak in a phase 1 image and the group code is G25. That must be line L193 on the illuminator array, unless there is an error and is actually group G24, misread. If this is the case, it is line L185. Alternately, it could be line L201 in group 26. However, the out-of-phase signal of binary pattern **48** is unambiguously high around line L193 and low around lines L185 and L201. Checking the out-of-phase signal verifies the group code for phases 1 and 8, as well as phases 2 and 7.

(iii) Keeping track of the group code associated with each peak on a row; from right to left, the group codes should increase monotonically. A code may be skipped, but the group number should not decrease. If a decrease is observed, a potential problem is indicated.

Dark and Flat Images

Dark and flat images **36** and **38** are obtained as described in the sequence of FIG. **3**. These images can be averaged to provide a measure of intensity that is used as a threshold to differentiate bright from dark intensities to help improve the signal mapping in pixel assignment step **44** (FIG. **3**).

It is noted that the sequence of image projections and recording can be followed in any suitable order for the methods of the present invention. Moreover, multiline images and binary patterns can be interspersed, rather than obtained in any fixed order.

FIGS. **15A** and **15B** compares results of processing using the method of the present invention for an uncoated tooth **90** and for a coated tooth **92**, that is, a tooth coated with a powder or other material, as is needed with conventional tooth surface imaging systems that have been commercially available. As shown, results for uncoated tooth **90** compare favorably to those for coated tooth **92**, without the need to prepare the tooth.

FIG. **16** shows a difference map **98** from combining the images for uncoated and coated teeth **90** and **92**.

Forming a group mapping helps to resolve potential ambiguities in depth measurement. Embodiments of the present invention help to provide robust methods for group map generation without requiring projection, detection, and processing of an excessive number of binary images. The logic flow diagram of FIG. **17** shows a sequence of image projection, detection, and processing steps used for surface contour detection and executed at least in part on a computer according to an embodiment of the present invention. In an image capture step **40**, the operator positions the imaging apparatus and captures a series of images, as described subsequently. The images consist of a number of group index images **102** and optional block images **104** and a number p of multiline images **54** and can be captured in any order. Once the images are captured, a pixel assignment step **44** executes, in which pixels on the image sensor array are assigned to a group map that corresponds to pixels on the illumination array. Images for the group mapping are from group index images **102** and block images **104**, described in more detail subsequently. An additional dark image **36**, with no illumination, and flat image **38** with full frame illumination are also obtained to help characterize the response of the sensor pixel array in signal processing, as described subsequently. A set of p multiline images **54** is also obtained, from which peak locations, that is, locations of highest intensity, can be detected in a location detection step **50**. A mapping step **60** then forms and stores the contour image in a memory, such as in a temporary display memory that is associated with a display monitor, for example. The resulting contour image can then be displayed or further processed.

FIG. **18A** shows the illumination pattern that is projected in one of the optional block images **104**. By way of example, FIG. **18B** shows a corresponding tooth image **114** that is obtained from projection of block image **104**.

FIG. **19A** shows the illumination pattern that is projected in one of the group index images **102**. By way of example, FIG. **19B** shows a corresponding tooth image **112** that is obtained from projection of group index image **102**.

FIG. **20A** shows the illumination pattern that is projected in one of the multiline images **54**. By way of example, FIG. **20B**

shows a corresponding tooth image **116** that is obtained from projection of multiline image **54**.

Embodiments of the present invention can employ different group sizes and arrangements, including specification of which sets of groups have pixels illuminated at any one time. For the sake of simplicity in the description of the image patterns that follow, an arbitrary group size of 8 pixels is used. The behavior of 128 pixels, in 16 groups with 8 pixels per group, is described. The 16 groups form an ordered set, in the terminology used herein. It can be appreciated that changes can be made in group size or in the number of groups that are members of an ordered set, within the scope of the present invention. The description that follows uses these exemplary values in differentiating group index images from multiline images.

FIGS. **21A** and **21B** compare group index and multiline images, respectively, with respect to the group arrangement for a single row of pixels **130** on illumination array **10**. Enlarged portion E1 shows a portion of the row that is greatly enlarged to indicate groups, with representative groups G1, G2, G3, G4, and G12 labeled by way of example. Two lines **120** and **122** of group index image **102** are formed by illuminated pixels in groups G4 and G12, respectively. Using this pattern, each line in group index image **102** is similarly formed by energizing a portion of the pixels in every 8th group. For the multiline image **54** in FIG. **21B**, by comparison, as shown in enlarged portion E2, each line **124**, **126**, **128**, **129** . . . is formed by illuminating a single pixel from each group, with representative groups G1, G2, G3, and G4 shown.

The schematic diagrams of FIGS. **22A** and **22B** show a distinction between the group index image and the multiline image at the pixel level. Groups are numbered from right to left. Row of pixels **130a** of FIG. **22A** shows the pattern of illuminated pixels used for projecting group index image **104** (FIG. **21A**). Here, only a pair of adjacent pixels in groups G1 and G9 are illuminated; remaining groups G2-G8 are all dark (having no illuminated pixels). In a row of pixels **130b** of FIG. **22B**, within each of the representative groups G1-G9 shown, the pixel in the third position from the left is illuminated. Row of pixels **130b** thus forms a multiline image, such as that shown in FIG. **21B**.

In general, embodiments of the present invention operate by projecting and recording a sequence of two or more group index images, as was described with respect to FIG. **17**. With respect to each ordered set of k groups, each projected group index image has, in at least two of the groups in the ordered set, no illuminated pixels. In the arrangement shown in FIGS. **21A** and **22**, a center-to-center distance D , between illuminated pixels, spans 8 groups. Using a separation distance of sufficient length helps to reduce ambiguity between groups in the projected image. By comparison, row of pixels **130b** shows the illumination pattern for multiline imaging, with a single pixel illuminated for each group. Distance $D2$ between illuminated pixels spans 8 pixels in this arrangement.

In general, in each group index image, in fewer than $(k-1)$ groups of the ordered set of k groups, from 2 to $(p-1)$ adjacent pixels are illuminated. Thus, for an 8-pixel group, for example, where $p=8$, from 2 to 7 adjacent pixels can be illuminated in the group that has illuminated pixels. In practice, it has been found that the group index image works well when two or three pixels near the center of the group are illuminated; the illumination of pixels nearer the borders of the group is more likely to cause some confusion or ambiguity in detection.

Multiple group index images are projected in sequence. The complete sequence of projected group index images uses illuminated pixels from each of the k groups in the ordered

11

set. In one example embodiment, wherein each ordered set of groups has 16 groups of 8 pixels per group, a total of 8 group index images are projected. Each group index image projects two lines, spaced 8 groups apart, as described with reference to the example group pattern in FIGS. 22A and 22B.

Table 1 lists the illuminated pixels for each of the projected images provided using the method described with reference to FIG. 17. The example listing in Table 1 is for the first 128 pixels of the illumination array, using an ordered set of 16 groups with 8 pixels per group. A total of 8 group index images are projected. A total of 8 multiline images are projected. The given pattern is repeated for each subsequent 128 pixel grouping. It should be noted that images can be projected in any order. In addition, the decision to obtain the optional block images can be made dynamically, based on results from the group index image projection and recording. According to an embodiment of the present invention, an automated assessment of the group index images determines whether or not the block images 104 are useful.

Correlation of pixels in a multiline image to group mapping utilizes the sequence of group index images as a guide in determining the group assignment for individual pixels. The group index images provide reference data for this correlation, using techniques familiar to those skilled in the contour mapping arts. The optional block images (for example, FIG. 18A) help further by providing information that resolves ambiguities in group mapping. The correlation that is obtained can be stored in any number of ways, as is well known to those skilled in the data representation arts.

Light intensity for each image can be the same; however, there can be advantages to changing intensity for different image types. Suitable adjustment of intensity can help to reduce the impact of scattered light, for example. According to an embodiment of the present invention, block images are projected at 50% intensity; group index images are projected at 75% intensity; and multiline images are projected at full intensity. Other intensity variations can alternately be used.

As noted with respect to FIG. 17, block images 104 help to resolve possible depth ambiguities with group index images 102 and are optional. Shifting the second block image relative to the first helps to provide more accurate mapping of group assignments for light directed to the surface of the tooth or other object.

TABLE 1

Image Sequence Example for 128 Pixel Segment	
Image type	Illuminated pixels
Flat image 38	1-128
Dark image 36	none
Block image #1	1-64
Block image #2	33-96
Group index image #1	3-6, 67-70
Group index image #2	11-14, 75-78
Group index image #3	19-22, 83-86
Group index image #4	27-30, 91-94
Group index image #5	35-38, 99-102
Group index image #6	43-46, 107-110
Group index image #7	51-54, 115-118
Group index image #8	59-62, 123-126
Multiline image #1	1, 9, 17, 25, 33, 41, . . . (Note 1)
Multiline image #2	5, 13, 21, 29, 37, 45, . . .
Multiline image #3	3, 11, 19, 27, 35, 43, . . .
Multiline image #4	7, 15, 23, 31, 39, 47, . . .
Multiline image #5	8, 16, 24, 32, 40, 48, . . .
Multiline image #6	4, 12, 20, 28, 36, 44, . . .

12

TABLE 1-continued

Image Sequence Example for 128 Pixel Segment	
Image type	Illuminated pixels
Multiline image #7	6, 14, 22, 30, 38, 46, . . .
Multiline image #8	2, 10, 18, 26, 34, 42, . . .

(Note 1):

For multiline images, every 8th pixel is illuminated, as the sequences show.

Consistent with an embodiment of the present invention, a computer executes a program with stored instructions that perform on image data accessed from an electronic memory. As can be appreciated by those skilled in the image processing arts, a computer program of an embodiment of the present invention can be utilized by a suitable, general-purpose computer system, such as a personal computer or workstation, as well as by a microprocessor or other dedicated processor or programmable logic device. However, many other types of computer systems can be used to execute the computer program of the present invention, including networked processors. The computer program for performing the method of the present invention may be stored in a computer readable storage medium. This medium may comprise, for example; magnetic storage media such as a magnetic disk (such as a hard drive) or magnetic tape or other portable type of magnetic disk; optical storage media such as an optical disc, optical tape, or machine readable bar code; solid state electronic storage devices such as random access memory (RAM), or read only memory (ROM); or any other physical device or medium employed to store a computer program. The computer program for performing the method of the present invention may also be stored on computer readable storage medium that is connected to the image processor by way of the internet or other communication medium. Those skilled in the art will readily recognize that the equivalent of such a computer program product may also be constructed in hardware.

It will be understood that the computer program product of the present invention may make use of various image manipulation algorithms and processes that are well known. It will be further understood that the computer program product embodiment of the present invention may embody algorithms and processes not specifically shown or described herein that are useful for implementation. Such algorithms and processes may include conventional utilities that are within the ordinary skill of the image processing arts. Additional aspects of such algorithms and systems, and hardware and/or software for producing and otherwise processing the images or co-operating with the computer program product of the present invention, are not specifically shown or described herein and may be selected from such algorithms, systems, hardware, components and elements known in the art.

In the context of the present disclosure, the act of “recording” images means storing image data in some type of memory circuit in order to use this image data for subsequent processing. The recorded image data itself may be stored more permanently or discarded once it is no longer needed for further processing. An “ordered set” has its conventional meaning as used in set theory, relating to a set whose elements have a non-ambiguous ordering, such as the set of natural numbers that are ordered in an ascending sequence, for example.

It should be noted that the term “memory”, equivalent to “computer-accessible memory” in the context of the present disclosure, can refer to any type of temporary or more enduring data storage workspace used for storing and operating

13

upon image data and accessible to a computer system. The memory could be non-volatile, using, for example, a long-term storage medium such as magnetic or optical storage. Alternately, the memory could be of a more volatile nature, using an electronic circuit, such as random-access memory (RAM) that is used as a temporary buffer or workspace by a microprocessor or other control logic processor device. Display data, for example, is typically stored in a temporary storage buffer that is directly associated with a display device and is periodically refreshed as needed in order to provide displayed data. This temporary storage buffer can also be considered to be a memory, as the term is used in the present disclosure. Memory is also used as the data workspace for executing and storing intermediate and final results of calculations and other processing. Computer-accessible memory can be volatile, non-volatile, or a hybrid combination of volatile and non-volatile types. Computer-accessible memory of various types is provided on different components throughout the system for storing, processing, transferring, and displaying data, and for other functions.

The invention has been described in detail with particular reference to a presently preferred embodiment, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention. The presently disclosed embodiments are therefore considered in all respects to be illustrative and not restrictive. The scope of the invention is indicated by the appended claims, and all changes that come within the meaning and range of equivalents thereof are intended to be embraced therein.

What is claimed is:

1. A method for mapping a sensor pixel array to an illumination pixel array according to a surface, comprising:

forming a group mapping by assigning each pixel in a plurality of pixels on the sensor array to a corresponding group of an ordered set of groups on the illumination pixel array, wherein each group is p adjacent pixels on the illumination pixel array and each ordered set has k groups, by:

recording a sequence of two or more different group index images of a sequence of two or more different group index patterns projected onto the surface, wherein, with respect to each ordered set of k groups, each projected group index pattern has, in at least two of the groups, no illuminated pixels and in fewer than $(k-1)$ groups, has from 2 to $(p-1)$ adjacent illuminated pixels, and wherein the sequence of projected group index patterns uses illuminated pixels from each of the k groups;

recording at least p multiline images of at least p multiline patterns projected onto the surface, wherein each multiline pattern projects a line within each group of p adjacent pixels on the illumination pixel array;

correlating lines in the recorded multiline images with lines in the projected multiline patterns according to the group mapping; and

storing, displaying, or transmitting the correlation, wherein k and p are integers greater than or equal to 3.

2. The method of claim 1 further comprising:

generating surface contour data according to the stored correlation; and

displaying the surface according to the surface contour data.

3. The method of claim 1 wherein forming the group mapping further comprises projecting and recording at least a first and a second block image, wherein each block image has a pattern with a number m contiguous groups of pixels illuminated at the same time and m contiguous groups of pixels

14

de-energized at the same time, and wherein the pattern for the second block image is shifted from the pattern for the first block image by $m/2$ groups.

4. The method of claim 1 wherein the illumination pixel array is a liquid crystal device or is a digital micromirror array device, where each multiline pattern projects a line of 2- to $p-1$ pixels within each group of p adjacent pixels on the illumination pixel array.

5. The method of claim 1 where the sequence of two or more group index images comprises k group index images.

6. The method of claim 1 wherein forming the group mapping further comprises obtaining and recording at least one dark field image and at least one flat field image.

7. The method of claim 1, where less than half the groups in each ordered set of k groups have 2 to $(p-1)$ illuminated pixels.

8. The method of claim 1 wherein the surface is a tooth, where $k > p$.

9. The method of claim 1 wherein the adjacent illuminated pixels of the group index image include one or more pixels nearest the center of the group.

10. The method of claim 1 further comprising projecting the sequence of two or more group index images and the multiline images at different power levels.

11. A method for mapping a sensor pixel array to an illumination pixel array according to a surface, the method executed at least in part on a computer and comprising:

characterizing the response of the sensor pixel array by projecting and recording a dark image and a flat image;

forming a group mapping by assigning each pixel in a plurality of pixels on the sensor array to a corresponding group of an ordered set of groups, wherein each group is defined by a set of p adjacent pixels on the illumination pixel array and each ordered set has k groups, by:

(a) projecting and recording one group index image at a time from each set, wherein each group index image has from 1 to $(p-1)$ adjacent illuminated pixels, and successively repeating the projection and recording at least k times; and

(b) projecting and recording at least a first and a second block image, wherein each block image has a pattern with k contiguous groups of pixels illuminated at the same time and k contiguous groups of pixels de-energized at the same time, and wherein the pattern for the second block image is shifted from the pattern for the first block image by $k/2$ groups;

projecting and recording at least p multiline images onto the surface, wherein each multiline image projects a line within each group;

correlating lines in the recorded multiline images with lines in the projected multiline images according to the group mapping; and

storing, displaying, or transmitting the correlation, wherein k and p are integers greater than or equal to 2.

12. The method of claim 11 wherein the surface is a tooth.

13. The method of claim 11 wherein the adjacent illuminated pixels of the group index image include one or more pixels nearest the center of the group.

14. The method of claim 11 further comprising projecting the sequence of two or more group index images and the multiline images at different power levels.

15. The method of claim 11 further comprising:

generating surface contour data according to the stored correlation; and

displaying the surface according to the surface contour data.

15

16. The method of claim 1 where the sequence of two or more group index images comprises k group index images.

17. The method of claim 1, where in each of the group index images, each ordered set of k groups has only 1 group with 2 to (p-1) illuminated pixels.

18. The method of claim 1, where a center to center distance D between groups with illuminated pixels spans p groups.

19. The method of claim 1, where less than half the groups in each ordered set of k groups 2 to (p-1) illuminated pixels.

20. A method for mapping a sensor pixel array to an illumination pixel array according to a surface, comprising:

forming a group mapping by assigning each pixel in a plurality of pixels on the sensor array to a corresponding group of an ordered set of groups on the illumination pixel array, wherein each group is p adjacent pixels on the illumination pixel array and each ordered set has k groups, by:

projecting a sequence of two or more group index patterns and recording a sequence of two or more group

16

index images, wherein, with respect to each ordered set of k groups, each projected group index pattern has, in at least two of the groups, no illuminated pixels and in fewer than (k-1) groups, has from 1 to (p-1) adjacent illuminated pixels, and wherein the sequence of projected two or more group index patterns uses illuminated pixels from each of the k groups;

projecting at least p multiline patterns onto the surface and recording at least p multiline images, wherein each of the at least p multiline patterns projects a line within each group of p adjacent pixels on the illumination pixel array;

correlating lines in the recorded multiline images with lines in the projected multiline patterns according to the group mapping; and

generating a surface contour image of the surface using the correlated recorded at least p multiline images, wherein k and p are integers greater than or equal to 3.

* * * * *